Injection-Locked 28-GHz Oscillator Array with Disk-Cylinder Reflector

Mark J. Vaughan and Richard C. Compton

Abstract—**A 28-GHz endfire (modified Vivaldi) active antenna is described that contains a secondary, circularly polarized patch antenna for reception of an external injection-locking signal. Three of these devices are used to characterize an octagonal cylindrical reflector designed for creating an omni-directional transmitter suitable for use in point-to-multipoint communication systems. The experiments provide data that validates the approach used to simulate the azimuthal radiation patterns. These simulations are then extended to predict the patterns from a full eight-element array.**

I. Introduction

RECENTLY, a new power-combining approach has emerged for the generation of 360° beams suitable for wireless cellular base stations [1]. To create an omni-azimuth transmitter using an array of planar active antennas requires endfire antennas, such as tapered-slot antennas (TSA's). The direct approach to creating such a transmitter places these antennas along the circumference of a circular substrate [2] that has the oscillators or amplifiers located in the center [1]. In most potential applications (such as in proposed local multipoint distribution systems or wireless local-area networks), the elevation beamwidth would need to be confined within 10–20° of the horizon. This can be achieved by placing metal disks above and below the array [3].

Unlike in linear, broadside TSA arrays, the antennas in this circular array are angled, pointing apart 30°. This, in conjunction with the fact that the TSA's in the circular array can only be spaced as close as 1.1 wavelengths at the periphery due to the need to fit the active circuitry into the center, results in nulls in the array pattern. One solution to avoid these is to turn the antennas around and have them face a reflector located in the center of the array, as shown in Fig. 1. This reflector can have a polygonal horizontal cross section so that each antenna points at a flat surface, and consequently the images of the antennas, which are pointing outward, can be made as close together as desired.

In addition to eliminating nulls in the azimuthal pattern, this reflector approach allows the designer to tailor the elevation pattern. As demonstrated in the mechanically steered antenna of [4], such a central reflector can be made with a parabolic vertical profile (similar to an hourglass) to provide substantial focusing in the elevation direction. Alternatively, a simpler reflector structure can be made with flat sides on a polygonal cylinder and metal plates above and below to limit the elevation beamwidth. This is the reflector illustrated in Fig. 1. Optimization of the reflector design and feed location was reported previously [5].

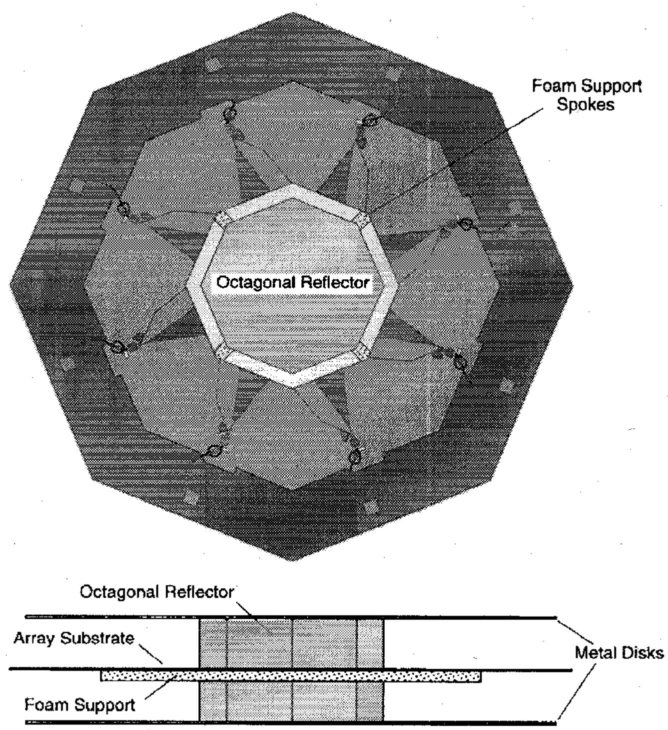

Fig. 1. Overhead view without the metal disks and side view of the proposed eight-element array. The array substrate is supported by a foam ring and spaced from the octagonal reflector by 3 mm. The separation between the top and bottom disks is two wavelengths.

An inherent advantage of the active oscillator approach is that elements can be optimized without building an entire array. In this letter, the construction and testing of a three-element sub-array is discussed, and from these results the performance of a full eight-element array can be extrapolated. The coupling between the oscillators is characterized, and this is used to determine the phases of operation for a full array. Further, the azimuthal patterns are measured for the individual elements and the three-element array to validate a technique for simulation of the patterns, which is then used to predict the pattern for the eight-element array.

Another issue that is addressed here is the use of external injection-locking as a means of reducing the phase noise

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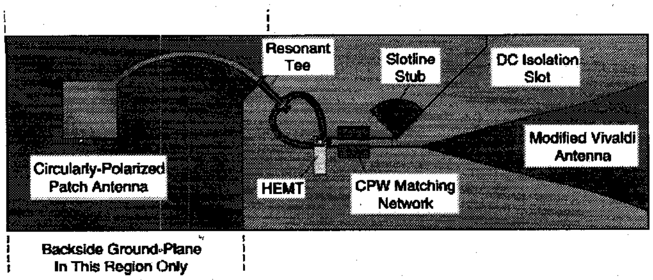

Fig. 2. Injection-locked 28-GHz active antenna. The injection-locking signal is received broadside by the patch, and the oscillator output is radiated to the right by the modified Vivaldi. Lighter shaded areas are metallized.

of the transmitter. Angle modulation plays a role in most modern digital communication systems, and phase noise is an important parameter in such cases. By injection locking an array of oscillators to an external, low-noise oscillator, the phase noise in the array can be substantially reduced [6]. For the work described here, a second antenna has been integrated into each active antenna circuit to receive an injection-locking signal.

II. Active Antenna Element

The active antenna used in this array work is shown in Fig. 2. It is identical to the oscillator element described in [5] with the addition of the circularly polarized patch antenna and the associated coupler, which allow controlled reception of an injection-locking signal. The oscillator circuit is constructed on 15-mil-thick Rogers TMM-3 ($\epsilon_r = 3.27$) and comprised primarily of coplanar-waveguide lines situated around an InP HEMT chip (gate periphery of 4×100 μm). Positive dc bias is applied to the drain through the portion of "ground-plane" to the right of the dc isolation slot, while the gate and source are grounded. The free-running frequency is determined mainly by the length of the "resonant tee" [7] and can be tuned by placing bond wires across the short-circuited end of the line. To transition between the CPW and the slotline used to feed the antenna, a quarter-wavelength slotline radial stub terminates one of the CPW slots [8]. Finally, the 28-GHz signal is radiated out the edge of the circuit from a shortened version of a Vivaldi TSA [9].

It was desired that a linearly polarized horn antenna be used to injection lock the oscillators in the array from above or below the reflector assembly. This puts the horn out of the way of the array's toroidal radiation pattern, but this means that the elements in the array receive different polarizations. For all the elements to have the injected signal be of the same amplitude, without individually tailoring their design, a circularly polarized, broadside antenna is needed. The corner-fed, nearly square microstrip patch of [10] and [11] was chosen for its simplicity. It was designed using a cavity mode analysis [12] to have dimensions of 2.67 mm × 2.53 mm, and the axial ratio was verified experimentally to be less than 0.5 dB over a range of 27.7–28.2 GHz.

Although the patch could have been placed on the back of the substrate and coupled to the CPW on the front through aperture coupling, this would require accurate alignment of the front and back lithography to achieve consistency between elements. With the layout chosen here, the only metal on the back is the microstrip ground plane, and the precise location of the edge of this metallized region is not critical.

To prevent a significant amount of the oscillator's output power from being radiated from the patch antenna, only a small degree of coupling (~ -10 dB) is desired from the patch antenna feed to the oscillator circuit. For this purpose, edge coupling is used between the microstrip line and the open end of the resonant-tee CPW line. The gap is roughly 25 μm across, which was experimentally determined to correspond to a coupling capacitance of approximately 3 fF.

For 28.0 GHz operation a typical dc bias for one of these oscillators is 2 V, 63 mA. Under these conditions, it was verified that the power density radiated in the broadside direction (in all polarizations) is at least 10 dB below that in the endfire direction of the Vivaldi. The oscillator is glued onto a foam post, which is a wavelength tall, at a distance of 3 mm from the surface of the octagonal cylinder. (These dimensions were previously determined to optimize the elevation (H-plane) pattern [5].)

III. Array Operation

With three oscillators mounted in the reflector and tuned to 28.0 GHz, the injection locking was tested as a function of the azimuthal angle (rotation about an axis normal to the plates). The locking range for a single oscillator varies from 2–29 MHz as a function of angle. This corresponds to a variation in the received locking power of about 6 dB ($\Delta f \propto \sqrt{P_{\text{inj}}}$) and indicates that the metal disk has a significant, polarization-dependent effect on the injection-locking signal. In future arrays a circularly polarized signal could be used for the injection locking to eliminate this problem, but for the purposes of this letter, the top plate is removed to eliminate the polarization dependence. (It has been verified that removing the disk does not significantly affect the E-plane patterns.)

Without injection locking, the strength of the coupling between two adjacent elements results in a locking range of about 200 MHz. When two adjacent elements with free-running frequencies of 28.00 GHz are locked together, the frequency of operation shifts to 28.09 GHz. These two measurements indicate that the phase of the coupling coefficient is on the order of $-60°$, which, in simulations of the full eight-element array with the closed-loop coupling, results in the array settling into a mode of operation with all the oscillators running in phase, as desired.

With all three oscillators locked together the frequency shifts to 28.10 GHz, which is consistent with the roughly $-60°$ coupling coefficient deduced previously. Fig. 3 shows the azimuthal (E-plane) pattern measured for this array and a simulation of the pattern computed using the patterns measured from each of the three oscillators operated singly at 28.00 GHz. This simulation models each of the active antennas as a point source image located at an effective radius of 10 mm from the center of the reflector. Because each of the flat sides of the octagonal reflector has a finite width (13.1 mm, or about 97° as seen from the simulated point source), representing the antenna-reflector combination by the antenna image is not

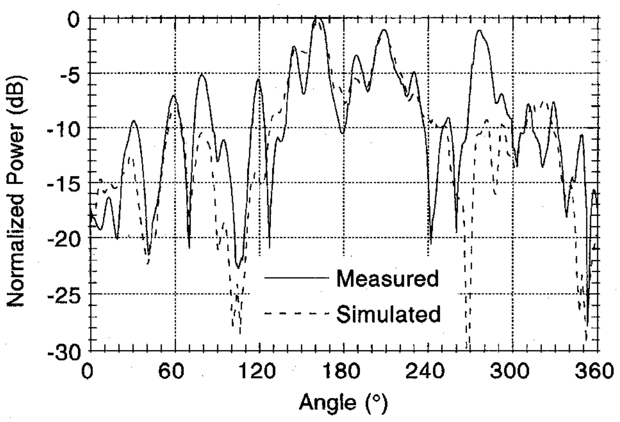

Fig. 3. Azimuthal pattern for the three-element array measured and computed from the patterns measured for the individual elements.

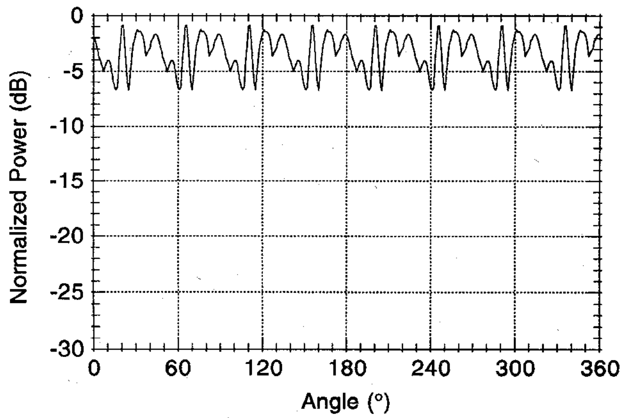

Fig. 4. An eight-element array azimuthal pattern computed using the single-element pattern data.

valid outside of a certain angular range. Consequently, the simulation shown in Fig. 3 was fitted only within ±45° of the reflected endfire direction of the middle element (187°). The resulting fit gives the operating phases between the adjacent oscillators to be 9° and 5° and validates this pattern simulation technique.

The technique is then easily extended to predict the azimuthal radiation pattern for the entire eight-element array. A difficulty arises in choosing the single-element pattern to use in the simulation, because the individual patterns for the elements used here vary significantly. In a final implementation of the array, greater uniformity will be achieved by more precisely locating the active antennas around the reflector and taking greater care in circuit fabrication to make the substrates more uniform. However, for the sake of showing the potential of this omni-directional array approach, the better of the three individual patterns was used in the simulation, with the effective radius optimized to 10.6 mm. The resulting pattern, shown in Fig. 4, is normalized to the maximum power from the single-element pattern. The radiated power here varies by only ±2.9 dB from 0°–360°.

IV. Summary

A 28-GHz endfire active antenna is demonstrated that contains a broadside, circularly polarized patch antenna for reception of an external injection-locking signal. An array of three of these oscillators is used to test an octagonal metal cylinder designed for producing an omni-directional transmitter with eight of the elements. The tests provide information on the mutual coupling and the injection-locking scheme and validate the technique used for simulating the E-plane radiation patterns. As a result it is demonstrated that this is a viable approach to creating an omni-directional radiation pattern with either oscillator or amplifier-based active antennas.

In the final, full implementation of this array, the injected signal will be circularly polarized, and consequently the patch antennas in the oscillators (or amplifiers) need only be linearly polarized. Also, greater uniformity of the individual elements' radiation patterns will allow the radius of the reflector to be tailored precisely to achieve a relatively flat azimuthal pattern, as predicted by simulation.

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